Photometry and Spectroscopy of the Optical Companion to the Pulsar PSR J1740-5340 in the Globular Cluster NGC 6397

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ABSTRACT

We present photometric and spectroscopic observations of the optical companion to the millisecond radio pulsar PSR J1740-5340 in the globular cluster NGC 6397. An analysis of the photometric variability in the B-, V-, and I-bands indicates an inclination of the system of 43.9 ± 2.1 degrees if the optical companion fills its Roche lobe (a semi-detached configuration). The spectroscopic data show a radial velocity variation with a semi-amplitude of $K = 137.2 \pm 2.4$ km/sec, and a system velocity $\gamma = 17.6 \pm 1.5$ km/sec, consistent with cluster membership. We use these results to derive a mass of the optical companion of $M_1 = 0.296 \pm 0.034\ M_\odot$ and $M_2 = 1.53 \pm 0.19\ M_\odot$ for the pulsar. There is evidence for secular change of the amplitude of the optical light curve of the variable measured over seven years. The change does not have interpretation and its presence complicates reliable determination of the absolute parameters of the binary.

1. Introduction

The millisecond radio pulsar PSR J1740-5340 was discovered in the field of the globular cluster NGC 6397 by D'Amico et al. (2001a) in the course of a survey conducted with the Parkes radio telescope. Follow up pulse timing observations (D'Amico et al. 2001b) led to a determination of several parameters of the system, including orbital period, projected semi-major axis and mass function. Ferraro et al. (2001) identified the optical companion of the pulsar with a variable object detected earlier by Taylor et al. (2001). Photometry presented by both groups shows that the optical companion to the MSP is a relatively bright star, $V_{max} \approx 16.7$, located slightly to red of the turn-off region on the cluster color-magnitude diagram. Remarkably, despite being located only $26''$ from the cluster center, the variable is a relatively isolated star (see Fig. 2 in Ferraro et al. 2001), permitting optical observations with ground-based telescopes. In this paper we present the results of photometric and spectroscopic observations obtained to determine the masses for both components of the binary.

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The evolutionary status of PSR J1740-5340 has been discussed by Burderi et al. (2002) and Ergma & Sarna (2002). Both groups present some detailed scenarios which attempt to explain the current status of the binary and the observed position of its optical component on the cluster color-magnitude diagram. The system has been detected in the X-ray domain with the *Chandra* observatory by Grindlay et al. (2001, 2002).

2. Observations

2.1. Photometric Observations

Observations in B, V, and I filters were obtained with the $2K^2$ TEK#5 CCD camera on the 2.5-m du Pont telescope at Las Campanas Observatory (LCO) in May and June 2002. The cluster was observed on 7 nights for a total of 32 hours. The camera has a pixel scale of $0.259''$/pixel. Only 600 rows of the CCD were read out during observations of the cluster in order to reduce dead time between exposures, resulting in a field of view of 8.65x2.60 arcmin^2 centered on the cluster.

Preliminary processing of the CCD frames was done with the IRAF-CCDPROC package.[4] For the photometric analysis we used stacked images each consisting of 3 to 8 individual short exposures. All co-added images span less than 10 minutes and in most cases less than 6 minutes. In the order of B, V and I-bands, the total number of stacked images is 69, 197 and 59, while average effective exposure times are 136 s, 75 s and 50 s. In the same order of the bands, the average seeing for the stacked images is $1.04''$, $1.03''$and $0.87''$.

We used the ISIS-2.1 image subtraction package (Alard & Lupton 1998; Alard 2000) to extract differential light curves of the optical counterpart of the pulsar, following the prescription given in the ISIS.V2.1 manual. For each band a template image was constructed from several stacked frames of the best image quality. Magnitude zero points for the ISIS differential light curves were measured from the template images using the DAOPHOT/ALLSTAR software package (Stetson 1987), and aperture corrections were measured with the DAOGROW program (Stetson 1990). Instrumental magnitudes were transformed to to the standard BVI system using the following relations:

$$V = v - 0.0134(B - V) + 0.1279(X - 1.25) + 0.7737 \tag{1}$$

$$B = b - 0.0690(B - V) + 0.2243(X - 1.25) + 1.1254 \tag{2}$$

$$I = i + 0.0059(V - I) + 0.0382(X - 1.25) + 1.3080 \tag{3}$$

where b, v and i are instrumental magnitudes and X is the air-mass. The coefficients of the transformation were measured from 12 observations of 5 Landolt fields (Landolt 1992) obtained on the night May 2 (UT). The standard fields were observed over a range of air-mass covering 1.16 to

[4]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.

2.00. Figure 1 shows the residuals of the photometric solution. We conclude that the uncertainties of the zero points of our photometry do not exceed 0.02 mag.

BVI light and color curves of the variable are presented in Figure 2 and Figure 3. We phased our observations using the ephemeris derived from radio timing observations from D'Amico et al. (2001b). The phase was shifted by 0.25 so that at phase 0.0 the optical component is in conjunction (in front of the radio pulsar).[5] Throughout this paper we use the ephemeris:

$$HJD(Min\ I) = 2\,451\,750.549336(7) + E \times 1.35405939(5) \tag{4}$$

where the numbers in parentheses represent formal 3σ uncertainties, in units of the last significant digit, of the very high precision determination of D'Amico et al. A program based on the KWEE algorithm (Kwee & van Woerden 1956) was used to determine moments of both minima for the phased light curves. It was found that after averaging the results for all 3 filters the observed photometric minima occurred 0.006 ± 0.004 of the orbital period earlier than times of minima predicted by the above radio ephemeris.

The phase coverage is generally good with the exception of the quadrature at phase 0.75 which is covered by only a few data points in the V filter and only single data points in the B and I filters. The light curves show symmetric minima and there is no indication for any significant difference in the light level at the two quadratures. The color curves show some reddening near phase 0.5. All of these features indicate that the observed variability is caused mostly, if not entirely, by ellipsoidal effects. In particular, the slight difference in the depths of the minima (with the secondary minimum being deeper) is consistent with such an interpretation.

In Table 1 we list BVI magnitudes observed at the extrema of the light curves as determined by parabolic fits to points located with phase ± 0.05 from a given extrema. The full amplitude of the light variation is 0.172(4), 0.152(4) and 0.139(5) magnitude for the B, V and I bands, respectively. We note that the HST observations collected in April 1999 indicate a noticeably larger amplitude. Taylor et al. (2001) report an amplitude of 0.21 mag in an unspecified band. However, the V band is the bluest of all bands they consider in their study. The lower limit on the amplitude of variation in the $H\alpha$ band was 0.20 mag from photometry published by Ferraro et al. (2001). We have extracted a V-band light curve of the variable from time series observations of NGC 6397 obtained in July 1995 with the 0.9m telescope at the CTIO (Kaluzny 1997). The data were reduced using the image subtraction technique, and the derived light curve is presented in Figure 4. The scatter visible in the light curve near phase 0.5 is consistent with the formal errors of the photometry. The zero point of the 1995 photometry was set to the zero point of the the 2002 data by comparing photometry of several stars located in the field of the variable. We conclude that in 1995 the amplitude of variability in the V band was about 0.23 mag and that the variable showed the same

[5]The ephemeris derived by D'Amico et al. (2001b) locates phase 0.0 at the ascending node of the pulsar orbit. This convention implies that for an inclination $i = 90\,\deg$ at phase 0.75, the observer sees the side of the companion facing the pulsar. In our convention the observer sees that side of the companion at phase 0.50.

level of maximum light in 1995 and 2002. However, the system was fainter at secondary minimum in 2002 in comparison with the 1995 observations. We comment on possible interpretations of these changes in the last section of the paper.

2.2. Spectroscopic Observations

Spectra were obtained with the B&C spectrograph on the 6.5-m Baade telescope at LCO on the nights of (UT dates) 30 May, 1 - 2 June, 8 June, and 29 July, 2002. The spectral resolution was 2.0 A, and the wavelength coverage was 3880 A to 5510 A (May and early June) and 3760 A to 5380 A (data taken on June 7 and July 29). The weather conditions were poor, with most of the data taken through clouds with seeing between 1.0 arcsec and 1.5 arcsec. The integration time for all exposures was 1800 seconds. Observations were also obtained of the velocity templates HD 74000 (sdF6, velocity = +204.2 km/sec) in May and June, and HD 116064 (sdF0, velocity = +143.4 km/sec) in July. These templates were selected from among low-metallicity stars to match the program star spectra.

Figure 5 shows a mean spectrum of the optical companion of PSR J1740-5340 from our observations on June 8 UT and July 29 UT, 2002, all shifted to the systemic velocity of the binary (see below). We also show for comparison a spectrum of the template star HD 74000. Despite the position of the optical system well off the cluster main sequence, the spectra of the stars are remarkably similar. The metallicity of HD 74000 is [Fe/H] = -2.07 (Beveridge & Sneden 1994) compared to the cluster metallicity of [Fe/H] = -1.95 (Harris 1996).

Velocities of the optical companion were measured using the RVSAO cross-correlation package (Kurtz and Mink 1998) running under IRAF, and errors were adopted from the XCSAO program. The results are given in Table 2. HD 74000 was used as the template for all of the May and June observations, and HD 116064 for the July observations. The relative velocity (HD 74000 $-$ HD 116064) was measured to be 56.2 ± 2.6 km/sec compared to our adopted value of 60.8 km/sec.

We made a least squares fit to the radial velocity data using GaussFit (McArthur et al. 1994), solving for the system velocity γ and the velocity amplitude of the optical companion. We assumed a circular orbit, and adopted the ephemeris given by Eq. (4). The results were $K_1 = 136.03 \pm 2.75$ km/sec, and $\gamma = 17.62 \pm 1.69$ km/sec. The heliocentric velocity of NGC 6397 is 19.2 km/sec (Gebhardt et al. 1995), and we conclude that this system is a cluster member. It has to be noted, however, that due to the non-spherical shape of the optical companion its radial velocity curve is expected to show some departures from purely sinusoidal motion. Therefore the above values of K_1 and γ have to be treated as first approximations only for further improvement in a combined photometric-spectroscopic solution given in the next section. The radial velocity observations are presented in Figure 6 using the ephemeris from Equation 4. Figure 6 also shows the GaussFit solution, and the velocity curve of the pulsar itself ($K_2 = 26.6121 \pm 0.0004$ km/s, as derived from the radio pulsar timing data, D'Amico et al 2001b) shifted to a systemic velocity of 17.6 km/sec.

3. Photometric and Spectroscopic Solutions

To solve the light and velocity curves of the optical component of the binary pulsar we used the Wilson-Deviney (1971, hereafter W-D) model as implemented in the 1986 version of the code. The code is described in some detail by Wilson (1979) and by Leung & Wilson (1977). The MINGA[6] minimization package (Plewa 1988) was used for the actual fitting of the observed light curves and the derivation of the system parameters. It was assumed that the only source of light in wavelengths covered by our data is the surface of the non-degenerate component. Using the T_{eff} versus $(B-V)$ calibration of Alonso et al. (1996) we estimated an effective temperature $T_1 = 5630$ K. Appropriate values of the limb darkening coefficients were taken from Wade & Rucinski (1985): $X_B = 0.679$, $X_V = 0.577$, $X_I = 0.40$. The gravity brightening coefficient was set to $g_1 = 0.32$, an appropriate value for stars with convective envelopes. The secondary component was assumed to be dark and very small so that it does not influence the shape of the light curve. This was achieved by setting $T_2 = 1000$ K and adopting a very high value of the gravitational potential $\Omega_2 = 900$.

There are some arguments for assuming that the binary is in a semi-detached configuration, filling its Roche lobe. This case is advocated by Burderi et al. (2002) who point out that a relatively high rate of mass loss of $\dot{M} \leq 10^{-10} M_\odot$ yr^{-1} is implied by estimates of the mass of the gaseous envelope causing the radio eclipses of PSR J1740-5340 to last about 40% of the orbital period. Further evidence supporting a semidetached configuration is the fact that the binary harbors an extended x-ray source, suggestive that the x-ray flux results from the interaction of a relativistic wind with mass loss from the optical companion (Grindlay et al. 2001). We show below that there is no evidence for heating of the optical companion by the MSP, and so the mass loss is likely to arise from Roche lobe overflow. In this case the mass needed to power the extended X-ray source could be supplied directly through the inner Lagrangian point.

However we cannot completely reject the possibility that the binary has a detached configuration, and in the following two sub-sections we present light and radial velocity solutions for both semi-detached and detached configurations.

3.1. Semi-detached configuration

The shape of optical light curves of the binary indicates that observed variability is dominated by ellipsiodal effect. Experiments show that the light curves can be in fact quite well approximated by a sine function. That means that any model used to reproduce the observed light curves could have no more than one free parameter, the sine-curve amplitude. In our light curve solution conducted for the assumed semi-detached configuration that free parameter translates into i, the inclination of the binary orbit.

[6]The MINGA package can be obtained from http://www.camk.edu.pl/∼plewa

We started the analysis by modeling the light curves with an assumed value of the mass ratio $q = m_2/m_1 = 5.11$, where the index 1 refers to the optical component, and where q is derived from the K amplitudes listed in the previous section. The W-D code was run in Mode-4, the configuration with the primary component filling its Roche lobe.

The solution converged to a model with inclination $i = 44.12 \pm 2.15$ degrees. The next step involved a determination of the radial velocity amplitude K_1 by fitting the observed velocity curve with model curves generated with the W-D code. The W-D code allows one to calculate the non-dimensional velocity curve, v_{1th}, and the K_1 amplitude is calculated using the relation:

$$v_{1obs} = v_{1th} \times K_1 \times sin(i) \times (1 + 1/q) + \gamma \tag{5}$$

where v_{1obs} is the observed photocenter velocity and γ is the systemic velocity. We derive $K_1 = 137.2 \pm 2.4$ km/s and $\gamma = 17.6 \pm 1.5$ km/s. This in turn gives a new value of the mass ratio $q = K_2/K_1 = 5.15$ which was used to get an improved solution of the light curves. This procedure converged after one more iteration and we derive the following set of final parameters: $i = 43.9 \pm 2.1$ degrees, $K_1 = 137.2 \pm 2.4$ km/s and $\gamma = 17.6 \pm 1.5$ km/s.

In Figure 7 we show the residuals for the final solution of the light curves. Note that while the fit is generally good, some systematic errors are present in fits obtained for the V and B bands at the level of 0.01 mag. These systematic errors cannot be corrected without introducing some additional features to the pure W-D model. The deviations have a tendency to diminish with increasing wavelength and indicate the presence of some extra light near phase 0.5 where we see the hemisphere of the optical component facing the pulsar. Some irradiation processes may be responsible for this effect. Figure 8 shows residuals for the model fit to the radial velocity curve. The observed residuals are consistent with the formal errors of the measured velocities. Figure 9 shows how the χ^2 statistic changes as a function of assumed inclination of the binary. The fit is excellent with a well defined minimum in χ^2 at $i \sim 44$ deg.

Using these values of the radial velocity amplitudes and the inclination we obtain masses of the components of the binary pulsar PSR J1740-5340 of $M_1 = 0.296 \pm 0.034\ M_\odot$ and $M_2 = 1.53 \pm 0.19\ M_\odot$. Note that the errors of the masses are dominated by the accuracy of the derived inclination. The absolute size of the orbit is $A = 6.30 \pm 0.09\, R_\odot$ and the average radius of the optical component is $R_1 = 1.67 \pm 0.02\, R_\odot$.

4. Detached configuration

In the detached configuration, the light curve of the system depends mostly on the inclination i and the gravitational potential Ω_1. These two parameters are strongly correlated and therefore we decided to obtain a grid of solutions for several fixed values of i. The results are given in Table 3 which lists the adopted value of inclination, the average relative radius of the optical component, its ratio to the inner Roche lobe radius, and the χ^2 of the model. Note that for a given mass ratio q, the radius r_1 is only a function of the gravitational potential Ω_1. Table 3 shows that fits of comparable quality were obtained for the whole range of adopted inclinations. In particular the solution for $i = 45$ degrees is very close to the semi-detached configuration considered in the previous section. Taken at face value, the fits for the detached case and $i >$ 50 are marginally better that the fit derived for the semi-detached case. Hence we believe that we cannot with confidence determine the configuration of the binary solely from the light curve solution. Table 4 lists some absolute parameters of the binary corresponding to the solutions from Table 3. Note that the formal errors of the masses in Table 4 do not include an uncertainty in the inclination as it was fixed for each entry in the table.

An additional and entirely independent constraint on the system inclination arises from information about its cluster membership. Reid (1998) and Reid & Gizis (1998) have used main-sequence fitting to derive V-band apparent distance moduli for NGC 6397 of 12.80 ± 0.1 and 12.69 ± 0.15, respectively. Adopting a distance modulus $(m - M)_{\rm V} = 12.72 \pm 0.18$ and using $< V >= 16.71$ (see Table 1) we obtain $< M_{\rm V} >= 3.99 \pm 0.18$ as an estimate of the average absolute magnitude of the optical component for an assumed reddening of $E(B - V) = 0.18$ (Reid & Giziz 1998). This gives $< M_{bol} >= 3.72 \pm 0.18$ for $BC = -0.27$ which is appropriate for the observed color and metallicity of the star (Houdashelt et al. 2000). Using the relation, $R/R_\odot = (L/L_\odot)^{1/2} \times (T_{eff\odot}/T_{eff})^2$, we obtain $R_1 = 1.68 \pm 0.14\, R_\odot$. This apparently eliminates all solutions with $i > 47$ degrees listed in Table 4.

A further constraint on the inclination could come from a measurement of the rotational velocity of the optical companion. Our spectra do not have high enough resolution, however the optical companion is bright enough that such measurements could be made with echelle spectrographs on 6.5-m class telescopes.

5. Discussion

An additional complication to the interpretation of the optical observations of the optical companion is the fact that its light curve clearly evolves on a time scale of a few years. The range of variability in the V band has changed from $\Delta V \approx 0.23$ mag in 1995 to $\Delta V \approx 0.15$ in 2002. We discuss briefly 3 possible interpretations of these changes.

1. *Secular change of the inclination of the orbit of binary*: Assuming a semi-detached configuration the observed change of ΔV requires a change of orbital inclination of about 8 degrees (from $i = 52$ deg in 1995 to $i = 44$ deg in 2002). There are a few eclipsing binaries with observed variation in the inclination of their orbital plane due to an interaction with a third body (Drechsel et al. 1994; Milone et al. 2000). However the rate of variation is at a level of a few tenths of a degree per year at best. Pulsar timing observations covering a 6 month interval (D'Amico et al. 2001b) show no evidence for a dynamical interaction of PSR J1740-5340 with a hypothetical "third body". Further radio timing observations of the pulsar should provide very strong limits on any

changes of orientation of the orbital plane of the binary.

2. *Variable "third light" contributions to the light curve*: Luminous streams of gas around pulsar or variable heating of the optical component of the system could lead to changes in the light curve. However in this case we should observe not only changes in the amplitude of the light curves but also changes in the maximum observed light. One may estimate how much of 3rd light is needed to diminish ΔV from ≈ 0.23 (1995 season) to ≈ 0.15 (2002 season), where ΔV is magnitude difference for phases 0.25 and 0.50. Denoting the flux level at phase 0.25 in 1995 season by l_{1V} we obtain $l_{3V} = 0.48\, l_{1V}$. That in turn implies that at quadrature the system would be brighter by 0.42 mag in 2002 season as compared with 1995 season. Our data show no indications for any change of light level at quadratures between the 1995 and 2002 seasons, which would exceed 0.02–0.03 mag.

3. *Intrinsic variability of the optical companion*: It is possible that the observed variability is intrinsic to the optical companion, perhaps in the form of star-spots. The companion has a high rotational velocity if it is tidally locked ($v_{rot} \simeq 50$ km/sec) and such a high rotational velocity in a fully convective atmosphere normally leads to the formation of star-spots. We have used WD code to perform some light curve simulations for a model including one dark spot. The starting point was the light curve solution obtained for the semi-detached configuration and the 2002 data. It turns out that one may indeed increase the depth of the minimum observed at phase 0.5 to 0.23 mag, as seen in 1995 season, by putting a dark spot in a region around inner Lagrangian point $L1$. Specific parameters of such a spot are $\Delta T = 1000$K and radius equal to 20 degrees (as seen from the center of the star). The corresponding change of V magnitude at quadratures would then amount to only 0.02 mag. It is worth to note in that context that light curves presented by Ferraro et al. (2001; Fig. 4) show a clear asymmetry at minimum light which occurs at phase 0.5. Spot hypothesis offers a possible way to explain such a distortion.

We do not have a definite explanation for the observed variations in the amplitude of the light curves. The hypothesis invoking stellar spots seems to be a viable option for a moment. Clearly further monitoring of the system would be desirable.

6. Summary

Our analysis indicates that the observed modulation of the optical light from the optical companion of the pulsar PSR J1740-5340 can be fully explained by ellipsoidal variations. There is no indication for any detectable light due to heating of the companion by radiation from the pulsar. However, the light curve amplitude appears to evolve on a time scale of a few years, a phenomenon without a clear interpretation which may systematically affect our results.

An analysis of the radial velocity curve indicates that, if the velocities are modeled with a simple sinusoidal variation, neglecting the non-spherical shape of the optical component, $K_1 = 137.2 \pm 2.4$ km/sec, and $\gamma = 17.6 \pm 1.5$ km/sec. The measured systemic velocity of the system is is consistent with cluster membership of the binary. Gebhardt et al. (1995) obtained for NGC 6397 $\gamma = 19.2 \pm 0.5$

and measured $\Delta V_{rad} \approx 5.0$ km/sec at radius $r = 30''$ from the cluster center. This observation is interesting in light of speculations about the possible formation of the system in a relatively recent three body interaction (eg. Grindlay et al. 2002).

The low amplitude of the observed light variations and lack of optical eclipses precludes a determination of the inclination of the orbit of the binary without making any assumptions. A well constrained solution for the light and velocity data (taking into account the photocenter velocity correction) was obtained by assuming a semi-detached configuration for the binary, resulting in $i = 43.9 \pm 2.1$ degrees for the system inclination and $M_1 = 0.296 \pm 0.034\, M_\odot$ and $M_2 = 1.53 \pm 0.19\, M_\odot$ for the masses of optical companion and the pulsar, respectively. Measurements of the masses of radio pulsars are know to show a remarkably narrow Gaussian mass distribution with $M = 1.35 \pm 0.04\, M_\odot$ (Thorsett and Chakrabarty 1999), and our measurement of the mass of PSR J1740-5340 is consistent with this result.

Relaxation of the assumption of a semi-detached configuration leads to light curve fits of similar quality for a wide range of inclinations, $44 < i < 90$ degrees. If we assume a bolometric correction of the optical companion of $BC = -0.27$ then the distance modulus of the cluster constrains the inclination to a range of $44 < i < 47$ degrees. In such a case our spectroscopic data give $M_2 \geq 1.31 \pm 0.06 M_\odot$ as a lower limit on the pulsar mass. The lower limit to the mass of the optical companion is $M_2 \geq 0.255 \pm 0.007 M_\odot$. The low mass of the optical companion of PSR J1740-5340 resulting from our analysis supports evolutionary scenarios presented recently by Burderi et al. (2002) and Ergma & Sarna (2002).

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Table 1: BVI magnitudes at extrema of light curves

Phase	B	V	I
0.00	17.504(3)	16.781(2)	15.832(3)
0.25	17.357(3)	16.647(3)	15.706(3)
0.50	17.529(3)	16.799(2)	15.845(4)
0.75		16.647(6)	

Note: Internal errors are given in parentheses.

Table 2: Radial velocities of the optical companion of PSR J1740-5340

HJD [a]	Phase	V[km/s]	σK
2424.579	0.785	-105.35	17.04
2424.598	0.798	-110.31	17.77
2424.625	0.818	-110.80	9.11
2424.652	0.838	-84.19	8.17
2424.676	0.856	-76.78	6.78
2424.704	0.876	-81.83	7.41
2424.729	0.895	-67.08	6.67
2424.763	0.920	-60.64	7.38
2424.787	0.938	-53.80	9.18
2424.815	0.959	-36.47	12.08
2424.839	0.977	-21.75	15.59
2424.877	0.004	7.81	16.79
2425.591	0.531	-3.34	11.43
2425.615	0.550	-30.00	18.01
2425.878	0.744	-115.51	11.12
2426.567	0.244	151.80	11.17
2426.591	0.270	160.33	9.35
2426.615	0.288	157.36	10.92
2426.713	0.358	121.86	12.63
2426.736	0.388	117.63	14.28
2428.785	0.885	-78.08	7.40
2433.609	0.454	62.58	9.38
2433.858	0.637	-83.88	11.63
2484.499	0.032	50.19	4.63
2484.523	0.050	70.68	4.35
2484.553	0.072	73.76	5.62
2484.576	0.089	79.94	5.63
2484.600	0.107	90.81	7.44
2484.623	0.124	107.70	8.52
2484.654	0.147	130.84	8.62
2484.678	0.164	130.32	9.18

[a] HJD - 2450000.0

Table 3: Light curve solutions for detached configuration and fixed inclination

$i[deg]$	Ω_1	$< r_1 >$	$< r_1 > / < r_{1in} >$	χ^2
90	10.113(18)	0.201(7)	0.75	285
85	10.102(18)	0.210(7)	0.79	281
80	10.067(18)	0.212(8)	0.80	271
75	10.013(18)	0.215(8)	0.81	262
70	9.941(19)	0.219(8)	0.82	258
65	9.850(19)	0.224(8)	0.84	258
60	9.743(18)	0.230(9)	0.86	266
55	9.620(18)	0.239(10)	0.90	286
50	9.489(17)	0.249(10)	0.94	317
47	9.412(10)	0.257(5)	0.96	336
46	9.388(13)	0.259(7)	0.97	342
45	9.365(11)	0.263(7)	0.99	345

Table 4: Absolute parameters corresponding to solutions from Table 3

$i[deg]$	K_1	$A/R_\odot$	$< R_1 > /R_\odot$	$M_1/M_\odot$	$M_2/M_\odot$
90	136.2	4.38(6)	0.88(3)	0.099(3)	0.51(2)
85	136.2	4.40(6)	0.92(3)	0.100(3)	0.51(2)
80	136.2	4.45(7)	0.94(4)	0.104(3)	0.53(2)
75	136.2	4.53(7)	0.98(4)	0.110(3)	0.56(3)
70	136.3	4.66(7)	1.02(4)	0.120(4)	0.61(3)
65	136.3	4.83(7)	1.08(4)	0.133(4)	0.68(3)
60	136.4	5.06(7)	1.16(5)	0.153(4)	0.78(4)
55	136.5	5.35(8)	1.28(5)	0.181(5)	0.93(4)
50	136.7	5.72(8)	1.42(6)	0.222(7)	1.14(4)
47	136.8	5.99(9)	1.54(2)	0.255(7)	1.31(6)
46	136.9	6.09(9)	1.58(4)	0.268(8)	1.38(6)
45	137.0	6.20(9)	1.63(4)	0.282(8)	1.46(7)

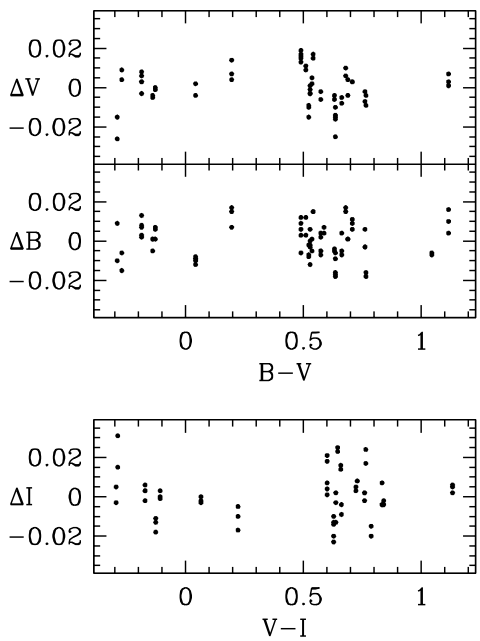

Fig. 1.— The BVI residuals of Landolt standard stars as a function of color resulting from transformations defined by Eqs. (1)-(3).

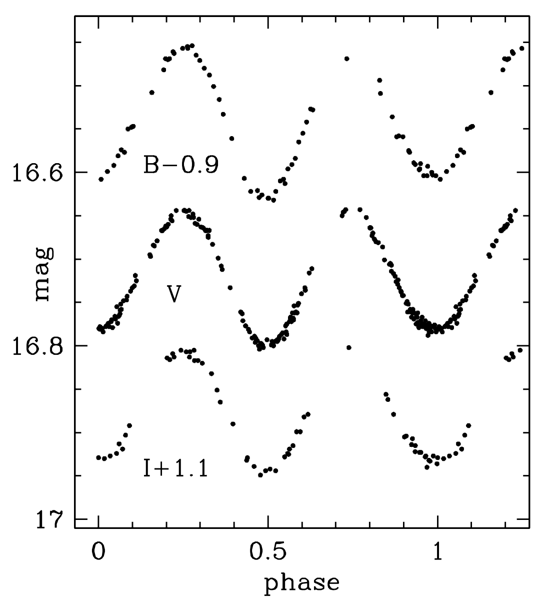

Fig. 2.— BVI light curves of the optical companion of the MSP PSR J1740-5340 obtained in May-June 2002. Note that the data for the $B-$ and I-bands have been shifted by -0.9 and $+1.1$ mag, respectively

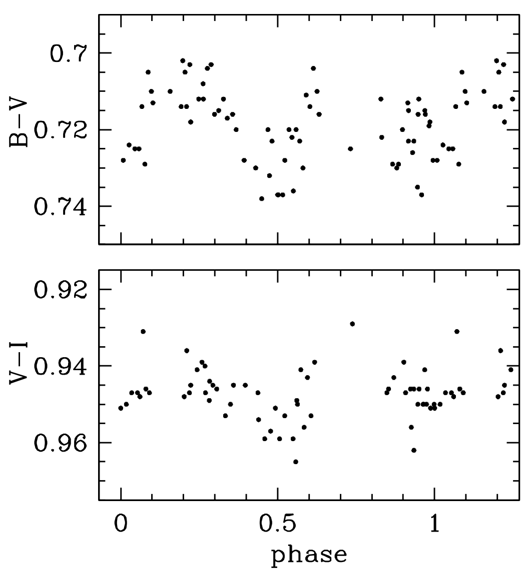

Fig. 3.— Color curves of the optical companion of the MSP PSR J1740-5340.

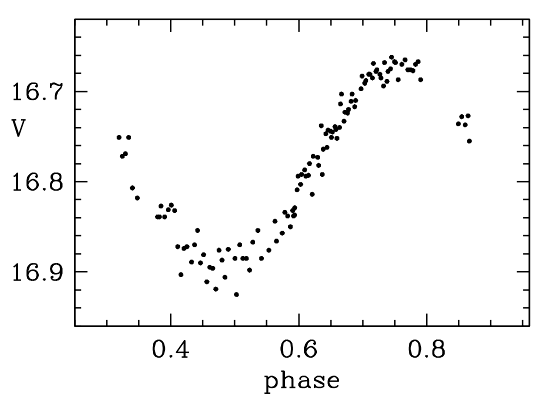

Fig. 4.— V-band light curve of the optical companion of the MSP PSR J1740-5340 obtained in July 1995.

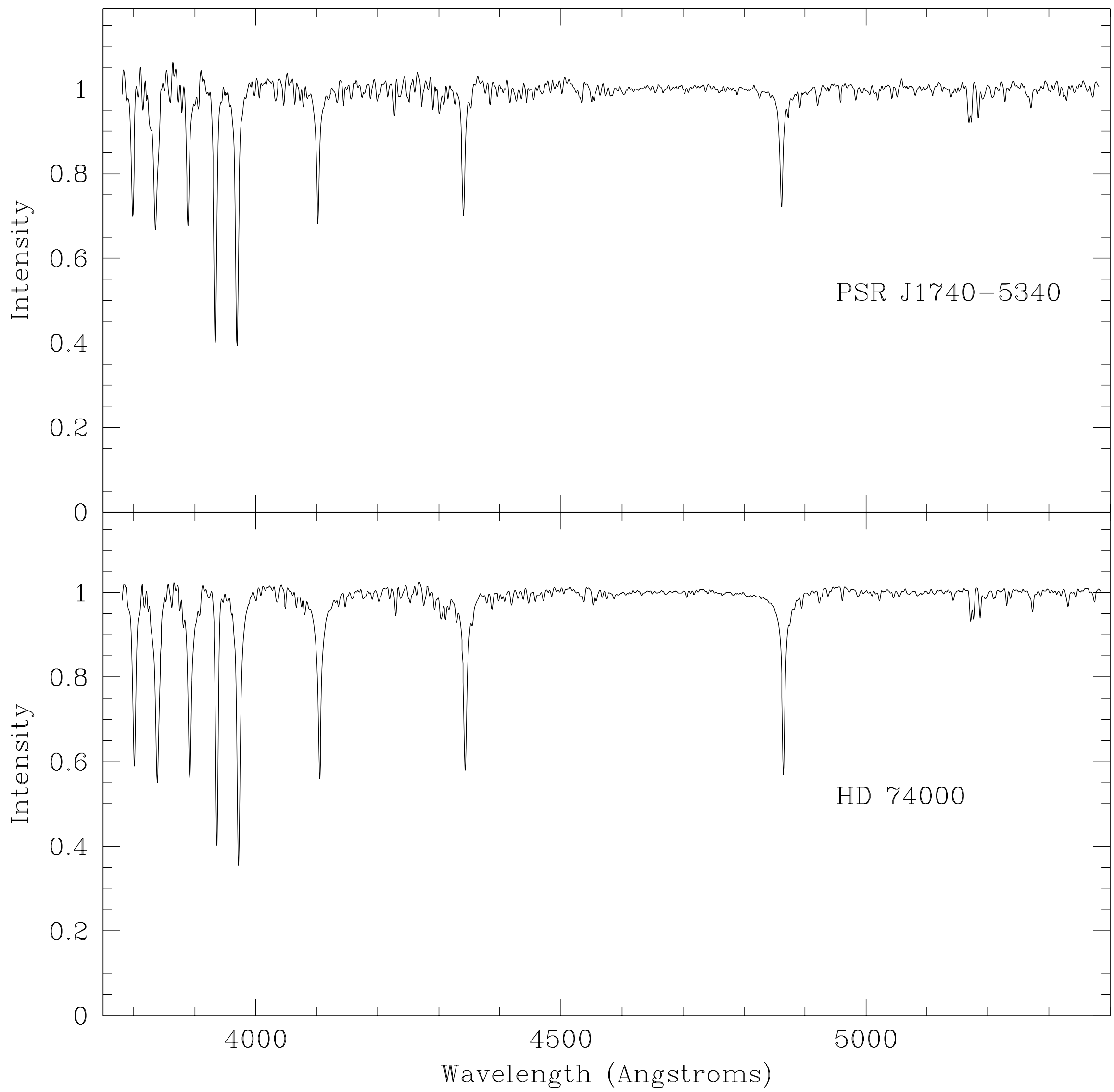

Fig. 5.— The mean intensity-normalized spectrum of the optical companion to PSR J1740-5340 (top) together with a spectrum of the velocity template HD 74000, spectral type sdF6 (bottom).

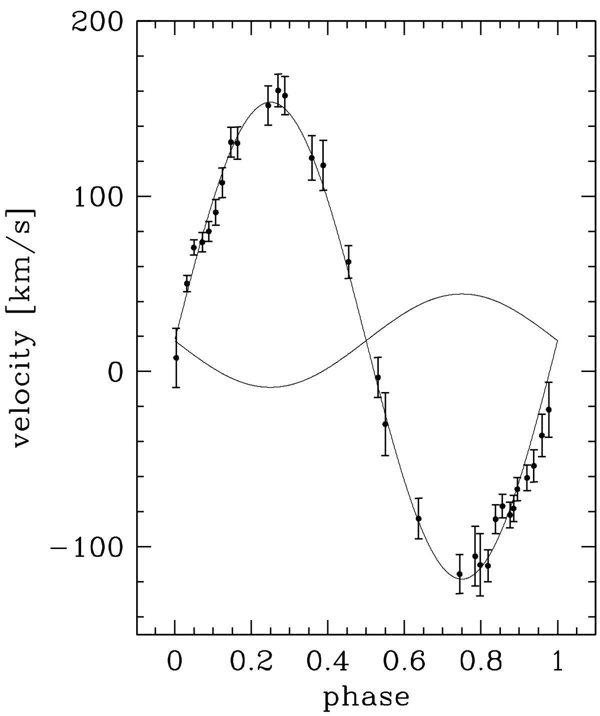

Fig. 6.— The radial velocity measurements plotted with the circular orbital solution. The low amplitude curve represents the orbital motion of the pulsar as derived from timing observations.

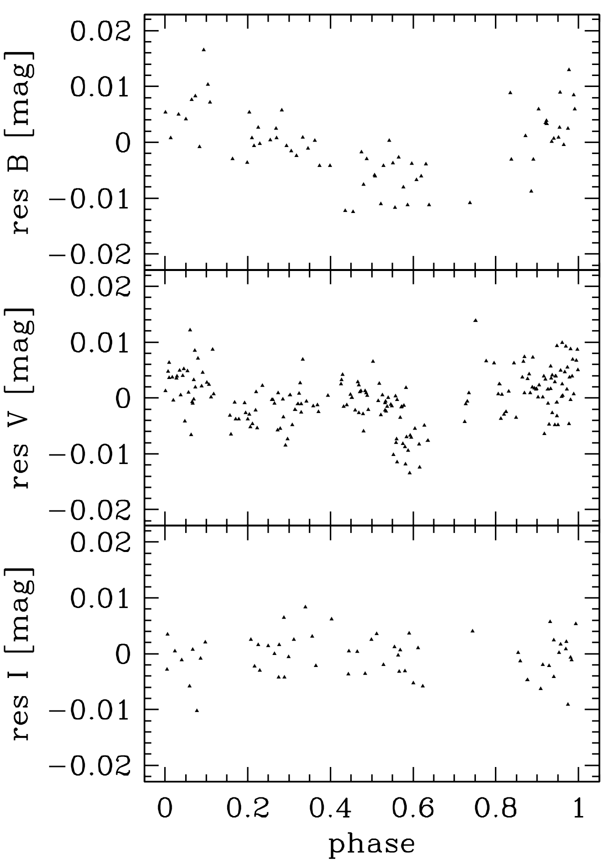

Fig. 7.— $O - C$ residuals for the photometric solutions of the BVI light curves.

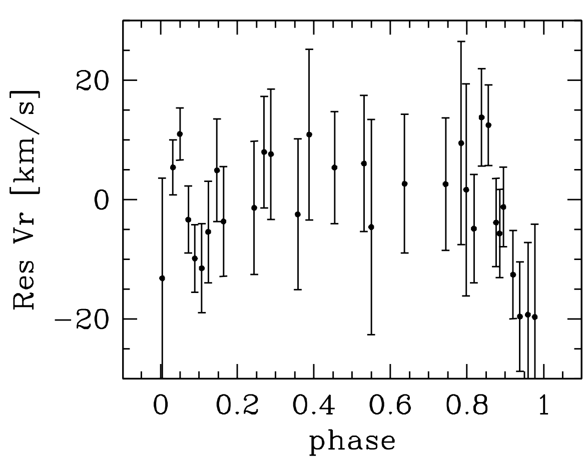

Fig. 8.— The radial velocity residuals (observed minus calculated) for the model corresponding to semi-detached configuration

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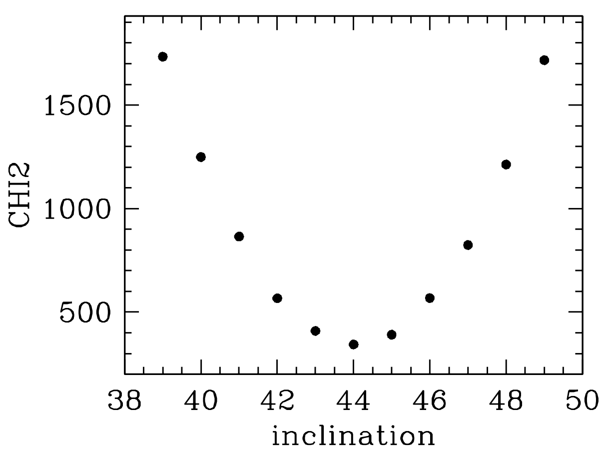

Fig. 9.— χ^2 statistic for light curve solution as a function of assumed inclination.